Calibration of five-axis machine tool using R-test procedure

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Abstract

Geometric calibration of five-axis machine tools is presently a very complex procedure, since most measuring devices are restricted to acquiring of individual errors. Industrial experience shows that several days are required for the complete metrological examination of a five-axis machine tool. In this paper, a method based on R-test is presented that allows the complete geometric calibration of compact machining centers with swivelling rotary table within a few hours. This advance in calibration speed is achieved by the combined indirect measurement of all geometric errors with a contactless 3D measurement probe attached to the tool holder of the machine and a reference ball attached to the table. With the newly developed method, almost all errors of linear axes and rotation axes can be calibrated.

For the calibration method, a model of the machine errors and the measurement process is required. The position of the sensor at the TCP (Tool Center Point) and the ball on the rotary table are modelled based on the rigid body theory. Each error motion is modelled as a function of their related axis position. A measuring strategy is defined to allow the numerical identification of all relevant errors with minimum measuring effort. For this purpose, measurement data from several ball positions has been used as training and test data.

Several error models are defined and tested to compare their performance. For analysis of the calibration quality, the geometric errors of a test machine tool are compensated and two methods are used to measure the residual error: 1) R-test at independent ball position. 2) Circular test in three coordinate planes. Based on the results, the optimal error model for the test machine is decided.

1 Introduction

5-axis machining is a key technology for the manufacturing of molds, turbine components in aviation, prosthesis in medical technology and engine in the automotive sector. Compared to 3-axis machine tools, high component complexity and also significantly higher automation levels can be achieved by the elimination of re-clamping operation. By eliminating the re-clamping processes, higher precision on the component is also achievable. However, the simultaneous movement of five axes creates more origins of error and the achievable processing accuracy is often not sufficient.

During quasi-static operation (under low thermal and dynamic load), the machining accuracy is decisively determined by the geometric errors of axes. These errors are classified into two groups [1]:

- Location and orientation errors: Position independent errors which describe the deviant location and orientation of movement axes.
- Error motions: Position dependent errors which describe the axis motion deviation. Usually an interpolation method is necessary to model these errors.

A well-known approach for optimization is metrological detection and compensation of these errors which is defined as calibration. The error measurement methods are classified into two groups:

- Direct method: Each particular error is measured individually.
- Indirect method: The deviation of the TCP/machine is measured as the combination of existing errors. Generally, a mathematical model of the machine and its errors is required.

A very good overview of the current state of calibration technology is available [2], [3]. However, a complete calibration of five-axis machine tools is still a time-consuming and complicated process due to the complex kinematics and many existing errors.

Bringmann et al. [4], [5] presented an indirect calibration method called 'R-Test' which uses a ball and a 3D-Sensor to identify the constant location and orientation errors of a 5-axis machine. Mayer et al. [6] and Mchichi et al. [7] developed the R-Test method to identify the location and orientation errors as well as the error motions. For interpolation, the error motions are modelled as a polynomial function. In addition to the normal R-test measurement procedure, a length standard is measured to provide a mathematically unique solution.

This paper presents a method based on R-Test, which enables the complete calibration of the relevant errors of a 5-axis machine with swivelling rotary table (Figure 1). B-spline interpolation method is used to model the error motions. Several error combinations are defined to be identified for the comparison of the calibration results.

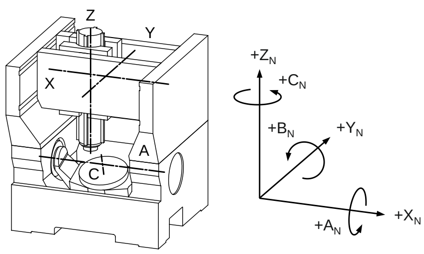


Figure 1: 5-axis machine with swivelling rotary table and its machine coordinate system

Thus, the second section of this paper introduces the modeling method of the five axis machine with information of the machine error model, B-spline interpolation method and kinematic modeling of the machine. In the third section, the calibration method is presented with the measurement device, measurement strategy and identification method. Afterwards, the measurement setup and measurement results are introduced with consideration on the best calibration method for the target machine.

2 Modeling of five axis machines

In this section, the mathematical modeling method of the 5-axis machine in Figure 1 is presented.

2.1 Machine error model

The location and orientation errors of the 5-axis machine can be reduced with a suitable definition of the machine coordinate system [1], [3]. In Table 1, the full error model of the target 5-axis machine tool is introduced.

Table 1: Full error model of the 5-axis machine tool in Figure 1

Error motions of the linear axes
EXX, EYX, EZX, EAX, EBX, ECX, EXY, EYY, EZY, EAY, EBY, ECY, EXZ, EYZ, EZZ, EAZ, EBZ, ECZ
Error motions of the rotary axes
EXA, EYA, EZA, EAA, EBA, ECA, EXC, EYC, EZC, EAC, EBC, ECC
Squareness errors of the linear axes
C0X, A0Z, B0Z
Location and orientation errors of the rotary axes
Y0A, Z0A, B0A, C0A, X0C, Y0C, A0C, B0C

2.2 Modeling of error motion

Due to the position dependency, the error motion can only be applied on a defined position of the associated axis. Therefore, the error in other areas must be modeled or interpolated. In the calibration method of Ibaraki [8], linear interpolation is used for the error motions. Mchichi et al. [7] models the error motion as a polynomial of the third degree. In this paper, a “basis spline” interpolation method, abbreviated "B-spline", is presented to precisely model the error motions of the machine tool.

2.2.1 B-Spline

The spline interpolation models a function by interpolating piecewise the known points. The area between two known points is defined by polynomials. Equation (1) describes the basic B-spline function which is used in this paper to model the error motions [9], [10]. In this paper, B-spline 2nd degree is applied for the error motions.

$$E(x) = \sum_{i=0}^{n} P_i \cdot N_{i,p}(x) \tag{1}$$

- E(x) is the representation of the error motion at axis position x
- p is the degree of the spline interpolation
- P is the control points
- N is the basis function

The basis function N is defined in equations (2-3):

$$N_{i,0}(x) = \begin{cases} 1 & if\ x_i \leq x < x_{i+1} \\ 0 & otherwise \end{cases} \quad (2)$$

$$N_{i,p}(x) = \frac{x - x_i}{x_{i+p} + x_i} N_{i,p-1}(u) + \frac{x_{i+p+1} - x}{x_{i+p+1} + x_{i+1}} N_{i+1,p-1}(x) \quad (3)$$

2.2 Kinematic modelling

For R-test, the position of the sensor and the ball has to be modelled mathematically. The kinematic modelling methods of many axis machines using homogeneous transformation matrix are available in many papers [11], [12], [13]. Basically, the machine is divided into two kinematic chain for the tool side and the workpiece side regarding to the machine coordinate system (Figure 2).

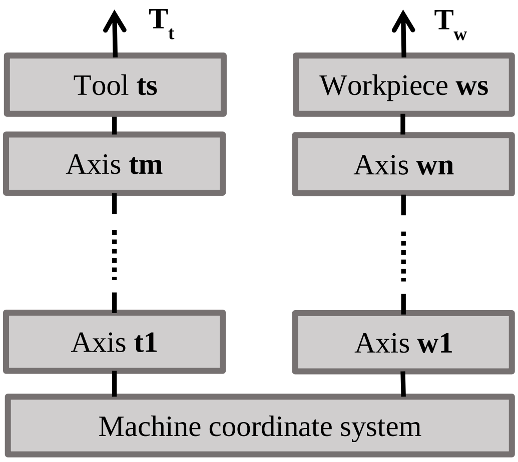


Figure 2: Kinematic modelling principle of 5-axis machine tools

The target machine has three linear axes on the tool side in the order of Y, X and Z axis and two rotary axis on the workpiece side in the order of A and C axis. The transformation matrices from the machine coordinate system to the sensor on tool side ${}^{MC}T_t$ and to the ball on workpiece side ${}^{MC}T_w$ are calculated in equations (4-5):

$${}^{MC}T_t = T_Y \cdot T_X \cdot T_Z \cdot T_s \quad (4)$$

$${}^{MC}T_w = T_A \cdot T_C \cdot T_b \quad (5)$$

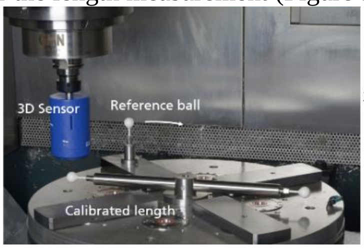
- T_X, T_Y, T_Z, T_A, T_C: Transformation matrix of each axis
- T_s, T_b: Transformation matrix of the sensor and the ball

To model the sensor measurement data, the transformation matrix from the sensor to the ball in sensor coordinate system is calculated in equation (6):

$$^{Sensor}T_{ball} = {}^{MC}T_t^{-1} \cdot {}^{MC}T_w \tag{6}$$

3 Calibration method

The 5-axis machine (Figure 1) which is used for the experiment has a movement range of the linear axes up to 1 m. The A-axis has a rotation range of ± 120° and the C-axis rotates over 360°. For the measurement device, the sensor and reference balls from IBS Precision Engineering are mounted on each tool and workpiece side (Figure 3). The sensor has 3 contactless eddy current sensors which measure the reference ball position in three dimensional coordinate system. Before the measurement, the sensor is calibrated with accuracy of 1 µm with measuring range of 1 mm. One length standard with two reference balls is used for the length measurement (Figure 3).



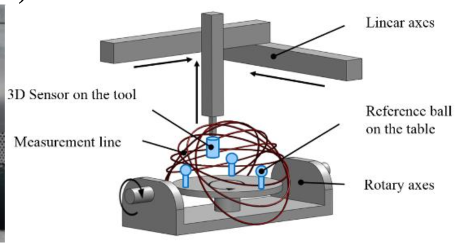


Figure 3: Measurement method using the 3D sensor and the ball from IBS Precision Engineering (left), Measurement process (right)

3.1 Measurement method

First, a reference ball is mounted at a suitable position of the table. For the initialization, the sensor on the tool side is positioned over the ball with a defined distance. The following measurement positions are defined after the positions of the rotary axes (Table 2). First the C axis moves from 0° to 360° with step width of 10° and the linear axes follow the rotary axes. This process is repeated for the position of the A axis from -60° to 60° with the defined step width. At each position the 3D distance between ball and sensor is measured. The measurement process is repeated for several ball positions. The measurement lines in Figure 3 show the movement of the ball during the measurement process. The length measurement is done at the zero position of both rotary axes.

Table 2: Measurement strategy

Rotary axis	Start position	Step width	Number of steps
C	0°	10°	36
A	-60°	10°	12

3.2 Identification method

The machine is mathematically modelled at the measurement positions. The error budgets in Table 3 are used for the analysis of the calibration results.

Due to their small effects, the angular errors of the rotary axes, Z-axis and one of the Y-axis are neglected [14]. With the linearisation of the model, the simple equation (7) is achieved, which can be solved with standard mathematical calculation.

$$A \cdot x = b \tag{7}$$

- A: Kinematic model of the machine at measurement positions
- x: Unknown coefficient of the defined error budgets
- b: Measured values of the sensor

Table 3: Error budgets for the identification method

Budget number	Included errors (cumulative)
1	Y0A, Z0A, B0A, C0A, X0C, Y0C, A0C, B0C
2	C0X, A0Z, B0Z
3	EXX, EYY, EZZ
4	EYX, EZX, EXY, EZY, EXZ, EYZ
5	EAA, ECC
6	EXA, EYA, EZA, EXC, EYC, EZC
7	EAX, EBX, EAY, EBY, ECY

4 Experiment

In this section, the experimental setup, the validation method and the results are introduced. For validation, the volumetric deviation of TCP is tested with two different methods on the calibrated machine.

4.1 Measurement setup

Before the measurement, the warm-up process of the machine is done by performing movement cycles identical to those of R-test. The total measurement is done in one day. For the interpolation of error motions, the B-spline 2nd degree is applied. The detailed experiment process is described below:

- Measurement of R-Tests at 4 different ball positions and one length measurement
- Identification of the error budgets in Table 3 using the measurement data of 4 ball positions
- Analysis of the residuals of the measurement data related to the error budget

To compare the calibration results, the machine accuracy is validated for each error budget on the calibrated machine. The volumetric compensation system (VCS) from Siemens AG is used for error compensation. Two different validation methods following are defined:

- Dynamic measurement of R-test at an independent ball position

- Circular test of the linear axes in three coordinate planes with double ball bar (radius: 150 mm) as an independent measurement method

For the error budget 7, the error motions are identified with three different interpolations methods: Linear interpolation, 3rd degree polynomial and 2nd degree B-spline. The calibration results are compared at the end.

4.2 Measurement Result

The results of the measurement and calibration are presented for the defined error budgets (Figure 4). Three important numbers are taken for the comparison of the results:

1) Absolute maximum residual of measurement data after error identification. (Model Fit)
2) Absolute maximum TCP-deviation of the dynamic measurement of R-test after error compensation. (R-test)
3) Absolute maximum TCP-deviation from circular test on 3 coordinate planes after error compensation. (Circular test)

As the results show, the maximum TCP-deviation of the target machine is reduced by 50 µm with the compensation of the location and orientation errors of the rotary axes. With the compensation of the additional errors, the volumetric deviations become smaller except for error budget 7 which includes the angular errors of linear axes. This can be caused by the measurement uncertainties and the relatively high standard deviation of the angular errors of the linear axes. The calibration of all location and orientation errors (budget 2) already compensate the biggest part of the machine deviation. The best error budget for the calibration of the target machine is budget 6 which reduces the maximum machine deviation to 5-8 µm.

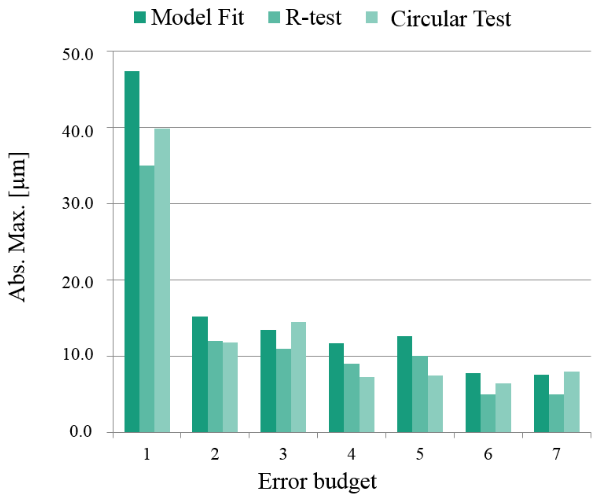


Figure 4: Experiment results for the different error budgets

For error budget 6, the dynamic measurement results of R-test on the target machine is presented. The uncompensated machine (

Figure 5) shows the deviation of almost 250 µm over the whole measurement process. The target machine is relatively old and relocated 2 times without any calibration which can cause such big volumetric deviations.

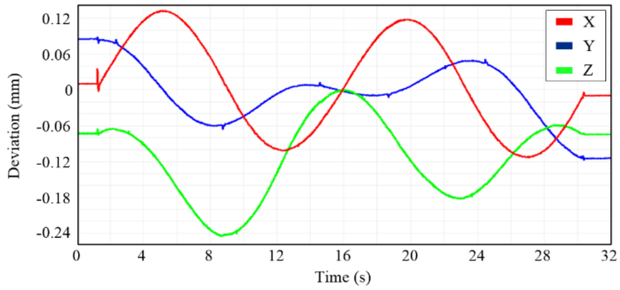


Figure 5: Dynamic measurement of R-test on the uncompensated machine

Figure 6 shows the dynamic measurement of R-test on the compensated machine with the error budget 6. Except for some dynamical deviation of the machine, which is shown by the few irregular peaks, a geometric machine accuracy of 5-6 µm is achieved.

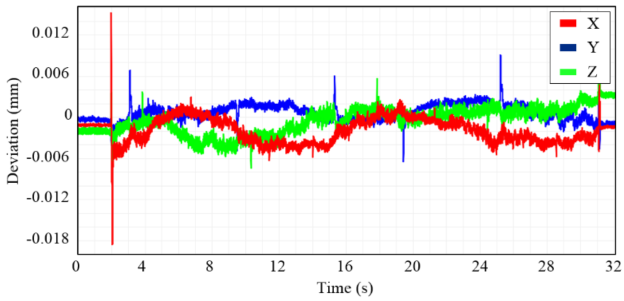


Figure 6: Dynamic measurement of R-test on the compensated machine

In Table 4, the comparison of the calibration results with different interpolation methods are shown for the error budget 7. Using the 3rd degree polynomials, the TCP deviations of the static R-test measurement at four ball positions are modelled with the smallest residuals. However, the maximum residual at an independent ball position (static R-test) is the smallest with the 2nd degree B-spline. The result shows that the 2nd degree B-spline could model the error motions more precisely than the other applied interpolation methods.

Table 4: Comparison of the interpolation methods for the error budget 7

Interpolation method	Max. residual of Model fit	Max. residual at an independent ball position (static R-test)
Linear interpolation	9.5 µm	5.2 µm
3rd degree polynomial	8.1 µm	6.9 µm
2nd degree B-spline	8.5 µm	4.1µm

5 Conclusion

In this paper, a method based on R-test is used for the calibration of the 5-axis machine with a swivelling rotary table. B-spline interpolation method is used for the error motions. The machine is mathematically modelled with homogenous transformation matrix based on the rigid body theory. A contactless 3D displacement sensor and reference balls were used for the measurement process.

A measurement strategy using 4 ball positions and a length standard is presented. Several error budgets are defined for the extensive comparison of calibration results. For validation, dynamic measurement of R-test on an independent position and circular test with a ball-bar was done for each error budget.

The proposed measurement strategy enables the full calibration of the relevant errors. Together with validation, the whole calibration process needs less than 2 hours for the target machine. The machine accuracy is achieved up to 8 µm with the defined error budget independent from axes position and measurement method. Compared to the linear interpolation and 3rd degree polynomial, the 2nd degree B-spline interpolation method shows the calibration results with the smallest residual TCP-deviations.

The applied measurement strategy could also be used for the other calibration methods with probing system such as Renishaw’s AxisSet or Heidenhain’s KinematicsOpt. However, the applied contactless measuring method provides direct 3D measurement of the ball position which could reduce the measurement duration enormously also regarding dynamic R-test. Furthermore, the method enables the measurement without any friction which could provide smaller measurement uncertainty.

The future work is focusing on validation of the calibration process on other 5-axis machines with the same kinematic configuration, machines with other kinematic types and optimization of the measurement strategy for a specified error budget in order to develop a standard R-test method for many applications.

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